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Reliability Evaluation considering Structures of a Large Scale Wind Farm

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Keywords

«Wind Farm», «Reliability Evaluation», «Structure», « power delivery ability», «Expected Power Delivery Ratio»

Abstract

Wind energy is one of the most widely used renewable energy resources. Wind power has been connected to the grid as large scale wind farm which is made up of dozens of wind turbines, and the scale of wind farm is more increased recently. Due to intermittent and variable wind source, reliability evaluation on wind farm is necessarily required. Also, because large scale offshore wind farm has a long repair time and a high repair cost as well as a high investment cost, it is essential to take into account the economic aspect. One of methods to efficiently build and to operate wind farm is to construct wind farm which is able to enhance a capability of delivering a power instead of controlling an uncontrollable output of wind power. Therefore, this paper introduces a method to evaluate the reliability depending upon structures of wind farm and to reflect the result to the planning stage of wind farm.

I. Introduction

The penetration of wind farm is growing at a high rate in global and in particular, Europe leads the establishment and operation of wind power plants. Under this circumstance, Korea is also planning to construct the large scale wind farm on the southwest offshore of the Korean peninsula.

The existing wind power plants were normally built on land as small scale distributed power supply system. However, in recent years, wind power plant has been connected to grid in the shape of large scale offshore wind farm. While offshore wind farm is able to gather wind energy with better quality in comparison to onshore plant [4], it has a higher repair cost as well as a higher investment cost. Therefore, it is essential to take into account the economic aspect when offshore plant is constructed [5]. The location of wind farm is preferentially decided at the area where wind speed is sufficiently high and stable, in order to increase the utilization rates of the wind farm. Due to the restricted location of wind turbine, the economic aspect may be applied upon structure of wind farm except wind turbine.

Many researches on evaluating the expected power of wind turbine have been done and various approaches have been developed [6]. However, if the scale of wind farm becomes larger, an effect of the failure can become also bigger, so that it could result in decrease of efficiency and economics of wind farm. Thus, based upon wind farm structure, it is required to identify potential failure and to evaluate the reliability of supply power of wind farm.

In this paper, reliability evaluation is performed considering failure of components contained to wind farm. For the purpose of evaluations, new two indices are introduced in this paper; one is 'the expected power delivery ratio' (EPDR) and the other is 'the expected power delivery ratio cost'(EPDRC). The EPDR means the ratio of the power which is able to be delivered to the grid, to the wind power generated at wind turbines. That is, The EPDR and EPDRC are the indices to present power delivery ability and its investment cost of wind farm.

The rest of the paper is organized as follows; factors influencing on the power delivery ability of wind farm are represented in Section II. In Section III, methods to evaluate the reliability and to calculate the indices are described. The case studies in Section IV show that the suggested indices can be considered as a significant role in planning of wind farm. Conclusions are given in Section V.

II. Basic Structure of Large Scale Wind Farm

Large scale wind farm can be considered as it consists of four components such as wind turbines, inner grid, transformer and external grid [3], [5], in the aspects of economics and reliability.

A. Wind Turbine

Large scale wind farm usually consists of dozens of wind turbines and recently it has been developed and operated up to a hundred of wind turbines. Generally, wind turbine has an output characteristic as shown in Fig. 1[3].

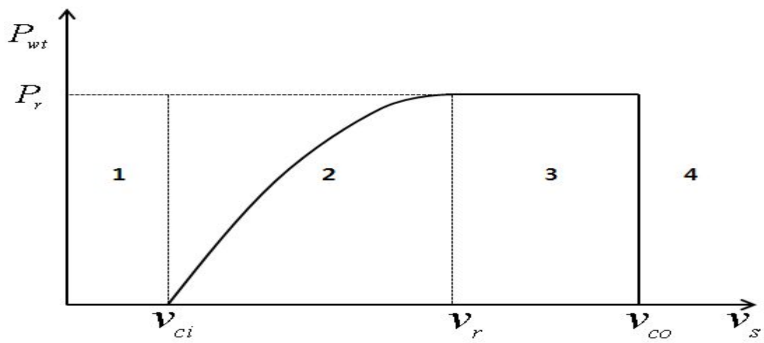

Fig. 1 The output characteristic of Wind turbine

In the first region, the output is zero due to very low wind speed. In the second region, as wind speed increases, wind turbine begins to generate power at the cut-in speed and increases the output continuously up to the rated wind speed. In the third region, the wind turbine maintains the rated output power. The wind turbine has zero in the region 4, due to the braking system for the protection of the wind turbine above the cut-out wind speed. The output P_{wt} of wind turbine can be approximated by the Equation (1).

$$\begin{aligned}
&P_{wt} = 0 && : 0 < V_s < V_{ci} \\
&P_{wt} = a + b \cdot V_s + c \cdot V_s^2 && : V_{ci} < V_s < V_r \\
&P_{wt} = P_r && : V_r < V_s < V_{co} \\
&P_{wt} = 0 && : V_{co} < V_s
\end{aligned} \tag{1}$$

where P_r, V_{ci}, V_r and V_{co} are the rated power output, the cut-in wind speed, the rated wind speed and the cut-out wind speed of the wind turbine, respectively.

B. Inner Grid

Once the location of dozens of turbines is decided, they are interlinked with offshore substation through inner grid. Depending upon voltage of inner grid and transfer capacity of lines, the number of feeders and wind turbines per feeder can be determined. More specifically, if the voltage of inner grid or the transfer capacity of line becomes higher, more wind turbines can be interlinked on a feeder due to the increased transfer capacity of the feeder, and it may reduce the investment cost due to the decreased length of total lines in inner grid. On the contrary, if any failure occurs at the beginning point of inner grid near substation, the power not delivered to grid may be more increased. Therefore, the number of feeders is treated as a major factor that influences the reliability and power delivery ability of inner grid.

C. Transformer and External Grid

Because of inner grid with a lower voltage, large scale wind farm has also a substation (transformer) and a high voltage external grid in order to deliver efficiently electric power to the grid [6]. When any failure occurs in transformer, it would limit the transfer capacity depending on either the number of transformers or its capacity. In addition, the transfer capacity could be possibly limited from failure of external grid, which is related to both cross sectional area and the number of lines. Therefore, both capacity and the number of transformers and lines of external grid are also treated as major factors.

III. Reliability Evaluation on Wind Farm

A. Indices for Reliability Evaluation

The purpose of this paper is to determine how to configure the wind farm in the efficient manner based on the reliability. Thus, the reliability evaluation is performed considering the failure of each component of wind farm as stated above, except the wind turbine in order to evaluate only the power delivery ability of wind farm.

Failure states represent all of the failures raised by failure factors in each component with the exception of wind turbine. Under each failure state, the power delivery rate (PDR) is defined as the ratio of output power of the component at failure state to input power at non-failure state, and is represented as follows.

$$PDR^{Comp}(f) = \frac{P_{Output}^{Comp}(f)}{P_{Input}^{Comp}(0)} \tag{2}$$

where f represents all the possible failure states, 0 means non-failure state. *Comp* represents the type of component such as inner grid, transformer and external grid.

The expected power delivery ratio (EPDR) of component is defined as sum of values obtained by multiplying PDR of each failure state and the corresponding probability as follows.

$$EPDR^{Comp} = \sum_{\forall f} PDR^{Comp}(f) \cdot \Pr^{Comp}(f) \tag{3}$$

where $\Pr^{Comp}(f)$ is the probability of f-th failure state.

The EPDR of entire wind farm ($EPDR^{WF}$) can be calculated by multiplying the EPDR of inner grid and EPDR of transformer and external gird, because they are considered as series connection.

$$EPDR^{WF} = EPDR^{I} \cdot EPDR^{T\&E} \tag{4}$$

where the superscripts *I, T&E* and *WF* mean inner grid, transformer and external grid, and the entire wind farm, respectively.

The EPDRC is NPV of investment cost per EDPR, which is defined as follows

$$EPDRC^{WF} = \frac{IC^{NPV}}{EPDR^{WF}} \tag{5}$$

where IC^{NPV} is the net present value of total investment cost (*IC*). EDPRC is slightly increased than the original investment cost because EPDR is less than 1. In this paper, the EDPRC means the reliability cost considering the failure effect of all components, which can be used as an index for determining the structure of wind farm based on investment cost related to power delivery ability of wind farm.

Fig. 2 shows a block diagram over the calculation procedure of the EPDR and EPDRC with the required data for the different structures of wind farm [5].

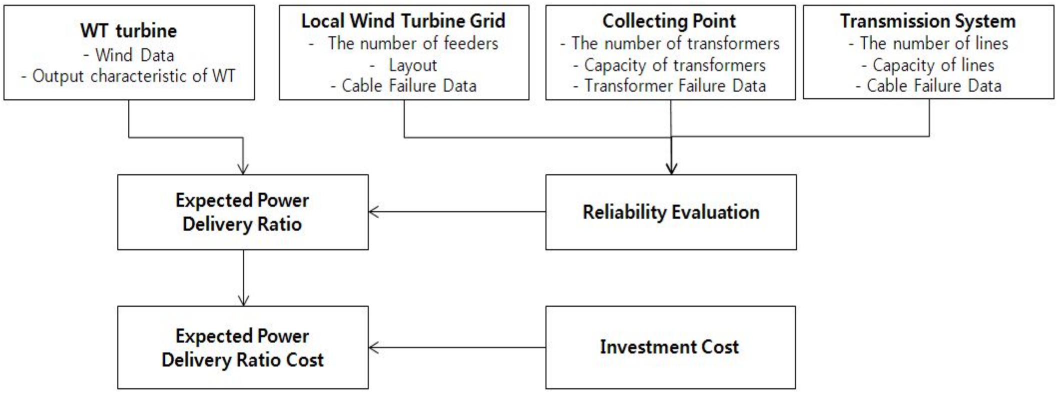

Fig. 2 Block Diagram for calculating indices

B. Reliability Delivery Rate on Inner Grid

At any failure state *k*, a vector is defined to represent the number of excluded turbines on each feeder

$$[fw_1(k),\dots,fw_x(k),\dots,fw_n(k)] \quad , \qquad 0 \le fw_x(k) \le fw_{x,Max} \tag{6}$$

where n is the number of total feeders, $fw_x(k)$ represents the failure point or the number of excluded wind turbines on feeder x ranged between 0 and the number $fw_{x,Max}$, which is the maximum number of wind turbine linked to the feeder when failure occurs on the beginning point of feeder near substation. Multiple failures in a feeder can be countered as a single failure at the nearest point to the transformer, because the number of excluded wind turbines is determined by the failure at the nearest point.

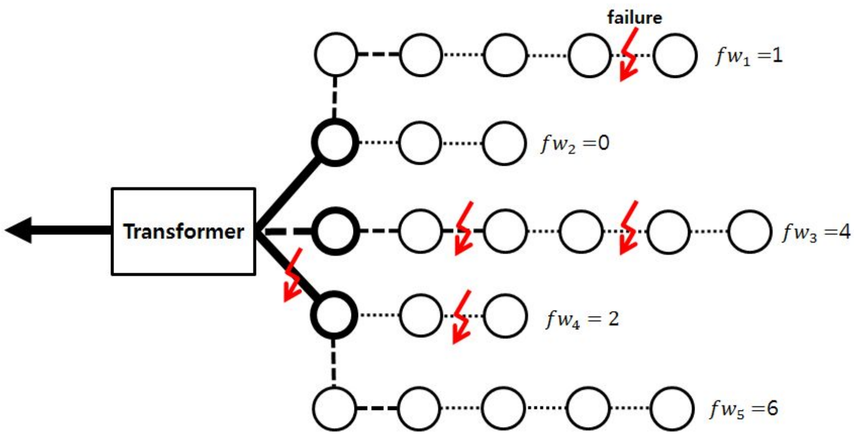

Fig. 3 Example of the failure state *k*

For instance in Fig. 3, inner gird consists of 5 feeders which have 6, 2, 6, 2, 6 wind turbines respectively, and feeders 2 and 4 are sub-feeders of the feeders 1 and 5, respectively. $fw_1(k)=1$ represents that a failure occurs at the end of feeder 1 and the number of excluded turbine is equal to 1. $fw_2(k)=0$ means that no failure occurs on feeder 2. Feeder 3 has two failures, but only the failure raised at the 4th point from the end is selected for $fw_3(k)$ and the failure at the second point is ignored. Feeder 4 is a sub-feeder and is connected to feeder 5, not directly connected to transformer. Although feeder 4 has a failure at the end of feeder, $fw_4(k)$ is 2 because feeder 5 has a failure at the beginning point, and all of turbines connected to feeders 4 and 5 are in outage state. As a result, a vector for the number of excluded turbine is represented as.

$$[fw_1(k), fw_2(k, fw_3(k), fw_4(k), fw_5(k)] = [1,\ 0, 4,\ 2,\ 6] \ . \tag{7}$$

In the same way, all of failure states can be organized, and then the number of available wind turbines is represented by the Equation (8).

$$
\begin{aligned}
NW^I(0) &= \sum_{x=1}^{n} fw_{x,Max} \\
NW^I(k) &= NW^I(0) - \sum_{x=1}^{n} fw_x(k)
\end{aligned} \tag{8}
$$

The failure of lines in inner grid and an output of wind turbines are independent each other. In other words, the input power delivered from wind turbines to inner grid is constant irrespective of the line failures because the wind speed blowing to all of wind turbines is assumed to be uniform moment by moment, while the output power transferred from inner gird to transformer, changes depending on the line failures. Input power to inner grid is the product of output of a wind turbine and the number of total wind turbines, and output power from inner gird is product of output of a wind turbine and the number of available wind turbines at any failure state. Therefore, the PDR of inner grid can be represented by the Equation (9).

$$
PDR^I(k) = \frac{P_{wt}(V_s)\cdot NW^I(k)}{P_{wt}(V_s)\cdot NW^I(0)} = \frac{NW^I(k)}{NW^I(0)} \tag{9}
$$

where $P_{wt}(V_s)$ is the output of wind turbine at wind speed V_s, which is assumed to be uniform at any moment over the entire wind farm area. As shown in Equation (9), the PDR of inner grid can be simply evaluated by dividing the number of available wind turbine at any failure state by the number of total wind turbine at non-failure state (k=0), which is independent of output of wind turbine.

The number of available wind turbines is equal to the number of line segments between the available wind turbines. If the availabilities of all the line segments are identical, then the probability of state k can be represented as (10), where, for the second term, the state of any segments behind faulted segment would not influence the probability

$$
\Pr^I(k) = A^{NW^I(k)} \cdot (1-A)^{NFF(k)} \tag{10}
$$

where A is an availability of each line and $NFF(k)$ means the number of faulted feeder with nonzero of $fw_x(k)$. Then EPDR of inner grid can be represented as

$$
EPDR^I = \sum_{\forall k} PDR^I(k)\cdot \Pr^I(k) \tag{11}
$$

C. Power Delivery Rate on Transformer and External Grid

The failure modes for transformer and external grid should be considered together, because the transfer capacity is limited by failure of transformer or external grid. When the maximum output of available turbines in inner grid is lower than the transfer capacity limited by transformer or/and external grid, the PDR becomes the unity because transformer and external grid can deliver all of the power injected from inner grid to the system grid, and otherwise, the PDR is less than the unity. That is, the power delivered to the system grid is dependent on both the supplying power from inner grid and the capacity limited by failure of transformer or external grid. Let inner grid and transformer and external grid are in the failure states k and g. For these specific failure states k and g, each wind turbine has the same maximum output as much as the value of transfer capacity limited by failure state g divided by the number of available wind turbines at failure state k. This value can be considered as a virtual rated power of each wind turbine at the failure states k and g, where the maximum of new virtual rated power is limited to the original one. It is illustrated in Fig. 4.

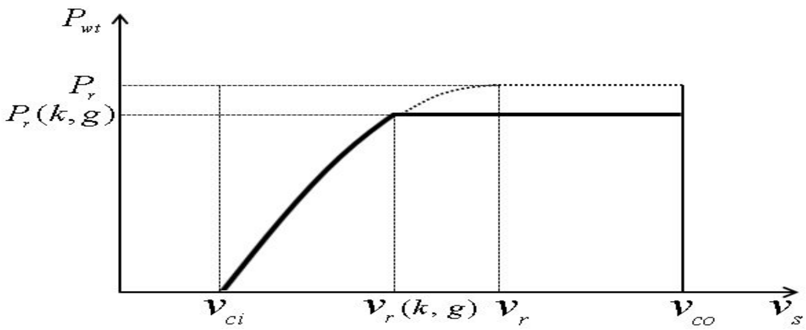

Fig. 4 output characteristic of wind turbine at the failure state k and g

In Fig. 4, the virtual rated power limited by failure states k and g is can be represented as follows

$$P_r(k,g) = \begin{cases} P_r & (P_r \le \dfrac{TC^{T\&E}(g)}{NW^I(k)}) \\ \dfrac{TC^{T\&E}(g)}{NW^I(k)} & (\dfrac{TC^{T\&E}(g)}{NW^I(k)} < P_r) \end{cases} \tag{12}$$

where $P_r(0,0) = P_r$, and $TC^{T\&E}(g)$ is transfer capacity limited by failure state g.

The expected output power of wind turbine at the states k and g can be obtained by multiplying the probability of wind speed and the power output at the corresponding wind speed as appeared in the output characteristic of wind turbine, where the rated power is replaced to new one as shown in Equation (13).

$$E(P_{wt}(k,g)) = \sum_{\forall S} P_{wt}(V_S) \times WP(V_S)$$
$$P_{wt}(V_S) = \begin{cases} 0 & : \mathrm{V}_S < \mathrm{V}_{ci} \\ P_{wt} & : \mathrm{V}_{ci} < \mathrm{V}_S < \mathrm{V}_r(k,g) \\ P_r(k,g) & : \mathrm{V}_r(k,g) < \mathrm{V}_S < \mathrm{V}_{co} \\ 0 & : \mathrm{V}_{co} < \mathrm{V}_S \end{cases} \qquad s = 0,1,2,\ldots,\text{cut-out} \tag{13}$$

where s is discretized wind speed state and $WP(V_S)$ is the probability of wind speed V_S. Then PDR in case of the failure state g and EPDR of the entire transformer and external grid can be obtained sequentially as Equations (14) and (15).

$$PDR^{T\&E}(g) = \sum_{\forall k} \frac{E(P_{wt}(k,g))}{E(P_{wt}(k,0))} \cdot P^I(k) \tag{14}$$

$$EPDR^{T\&E} = \sum_{\forall g} PDR^{T\&E}(g) \cdot P^{T\&E}(g) \tag{15}$$

A utilization rate is defined as a value divided the expected power by a capacity of wind turbine.

$$UR^{WT} = \frac{E(P_{wt})}{P_r} \times 100\% \tag{16}$$

where $E(P_{wt}) = E(P_{wt}(0,0))$. Also, utilization rate of the entire wind farm is represented as multiplying a utilization rate of wind turbine and the EPDR of wind farm.

$$UR^{WF} = UR^{WT} \cdot EPDR^{WF} \tag{17}$$

IV. Case Study

Case studies are performed on large scale wind farm of 125MW. The wind farm consists of 25 identical wind turbines with the rated power of 5MW. Each turbine has 1.733MW of expected output power based on wind speed obtained at the southwest coast in Korea. The utilization rate is 34.66% by Equation (16). Assuming that wind turbines have a sufficient separation distance each other in order to ignore the wake effect and wind speed is applied identically over all wind turbines, the entire wind farm has 379,485.13MWh as an annual expected energy.

Cases are established based on the number of feeders in inner grid as shown in Table I, and then each case is separated into the sub-cases according to the different structure and capacity of transformer and external grid as shown in Table II. All the cases can be configured by the combination of cases and sub-cases appeared in Tables I and II. For example, Case 1-1 is the case with 5 feeders in inner grid and the capacities of 125 MW for transformer and external lines. Figures 5, 6, 7 and 8 show the structure of each case. Inner grid of each case is designed with four kinds of lines with different cross sectional area in the economic aspect. In this paper, all sub-cases are studied for the Case 1 and only 1 and 3 sub-cases for the Cases 2, 3 and 4.

Table I: Configuration of Case 1, 2, 3 and 4

Case	1	2	3	4
No. of Feeders	5	4	3	5 (containing 2 sub-feeders)

Table II: Configuration of Sub-Cases 1, 2, 3 and 4

Sub case	- 1	- 2	- 3	- 4
Transformer	125MWx1	62.5Wx2	62.5MWx2	72.5MWx2
External line	125MW x1	125MW x1	62.5MW x2	72.5MW x2

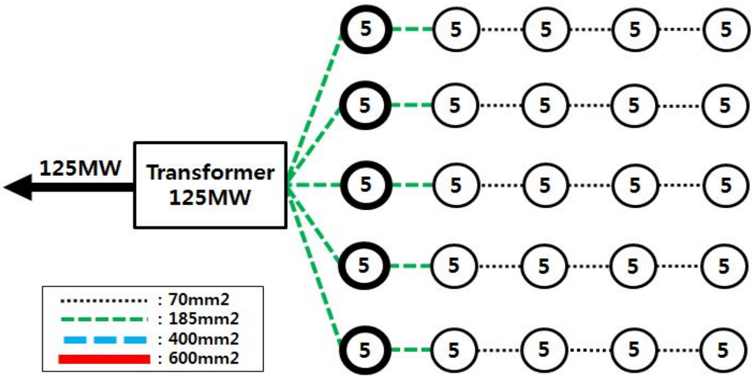

Fig. 5 Structure of Case1-1

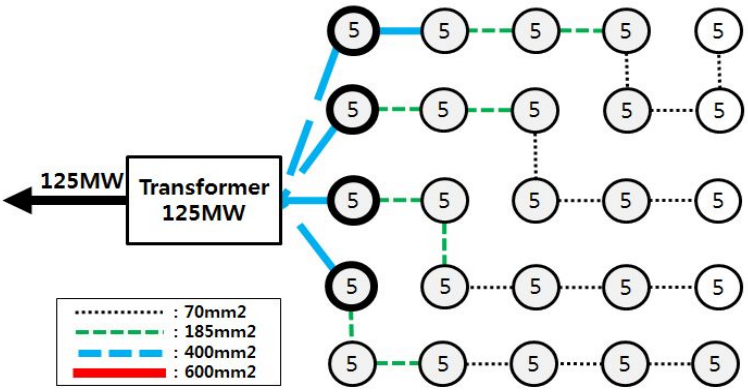

Fig. 6 Structure of Case2-1

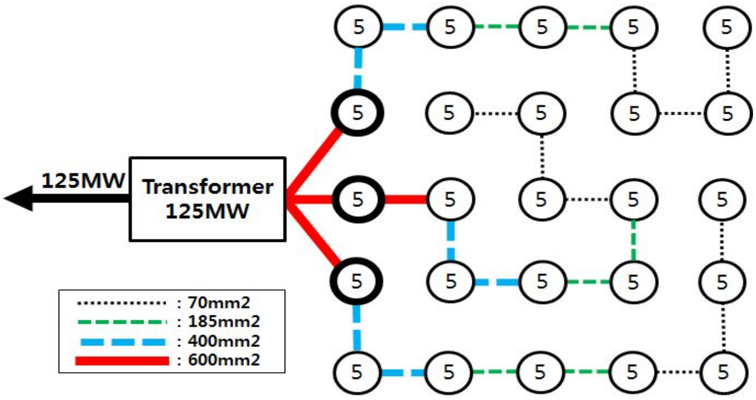

Fig. 7 Structure of Case3-1

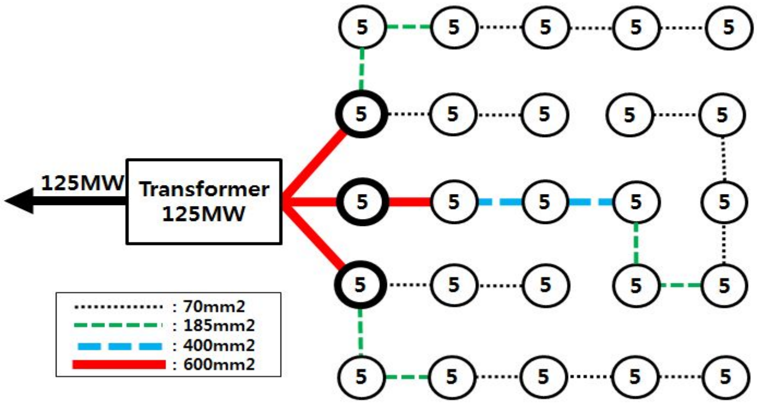

Fig. 8 Structure of Case4-1

It is assumed that the separation distance of each turbine is 1.12km in inner grid, and a length of transmission line is 26 km for external grid. The investment cost for each component of wind farm and the failure data are given in Tables III and IV, respectively.

Table III: Investment cost of each component

Inner grid		transformer		External grid	
Cross sectional area [mm^2]	Invest. cost [10^6 \$/km]	configuration	Invest. cost [10^6 \$]	Cross sectional area [mm^2]	Invest. cost [10^6 \$/km]
70	1.98	125MW×1	36.54	500	3.17
185	2.13	75MW×2	39.98		
400	2.28	62.5MW×2	37.62		
600	2.55				

Table IV: Failure date for line and transformer

	λ [occ/year]	r[year/occ]	Availability	Unavailability
Line	0.100	0.1644	0.9838	0.0162
Transformer	0.0667	0.3288	0.9786	0.0214

Table V: EPDR and Utilization Rate for Case 1

	EPDR			Utilization Rate
	Inner grid	Trans + External grid	Wind Farm	Wind Farm
Case 1-1	0.9525	0.9627	0.9170	0.3178
Case 1-2		0.9695	0.9234	0.3201
Case 1-3		0.9778	0.9314	0.3228
Case 1-4		0.9835	0.9368	0.3247

EPDRs of Case 1 are given in Table V. As shown in Table V, all EPDRs of inner grid are identical as 0.9525 since all sub-cases have the same configuration of inner grid. However, EPRDs of transformer and external grid and the entire wind farm are different according to sub-cases, and particularly, Case 1-4 has the highest the EPDR of 0.9368 as well as the utilization rate of 0.3247. As a result, it can be seen that the Case 1-4 is the most reliable structure in the aspect of the power delivery ability.

Table VI shows EPDRCs of Case 1. In order to calculate NPV of investment cost, the 20 year and 5% are used for warranty period of wind farm and discount rate, respectively.

Table VI: EPDRC for Case 1

	Total Invest. cost [10^6 \$]	NPV of invest. cost [10^6 \$]	Annual expected energy delivered [MWh]	EPDRC [10^3 \$/%]
Case 1-1	183.99	17.37	348,035.8	189.39
Case 1-2	185.06	17.47	350,475.1	189.17
Case 1-3	267.56	25.25	353,484.9	271.16
Case 1-4	269.92	25.48	355,529.0	271.99

As same as Table V, Table VI shows that the Case 1-4 has the highest EPDRC, and it may be considered as overinvestment. By contrast, Case 1-2 has the lowest EPDRC and can be considered as the most efficient structure in the economic aspect while Case 1-4 is the most efficient one in the aspect of reliability as explained in Table V. Annual expected energy delivered to the grid is calculated by multiplying the total capacity, utilization rate of wind farm and 8760 hours. It is the natural corollary that the more EDPRC, the more annual expected energy delivered, but the amount increased is insignificant compared with the increment of investment.

Table VII: Result of the rest of Cases

	EPDR of Inner grid	EPRD of Trans + External grid	EPDR of Wind Farm	EPDRC [10^3 \$/%]
Case2-1	0.9428	0.9627	0.9076	187.41
Case2-3		0.9782	0.9222	269.99
Case3-1	0.9272	0.9627	0.8927	185.73
Case3-3		0.9788	0.9076	269.59
Case4-1	0.9393	0.9627	0.9043	182.07
Case4-3		0.9784	0.9190	265.00

The results on the rest of cases are given in Table VII. As mentioned previously, it can be seen that if the number of feeders is decreased, the EPDRC may be decreased since investment cost of inner grid may be decreased due to the decrease of length of lines, whereas the outage capacity is increased so that the EPDR of inner grid may be also decreased. In addition, even though structure of transformer and external grid is identical, the EPDR can be affected depending on a configuration of inner grid.

V. Conclusion

Within the recent years, large scale wind farms have been widely prevalent. In general, the utilization rate of wind power has been estimated from the curve for wind turbine output and wind speed. However, since the size of wind farm became larger than previously, the reliability evaluation based on structures of wind farm composed of internal and external grid and transformers is required. From this viewpoint, this paper has calculated the expected power delivery ratio (EPDR) and cost (EPDRC) for comparison, depending upon the structures of wind farm. The case studies illustrate that the higher EPDR become, the more reliable the wind farm can remain itself, and also the lower EEDRC, the more economically the investment. Note that all those results can be used usefully in the planning stage to determine the wind farm structure in the aspect of economics and reliability at the same time, and there should be a trade-off between them.

References

[1] Roy Billinton, Ronald N. Allan.: Reliability Evaluation of Engineering Systems, 2nd ed. New York; Plenum Press,c, 1996.

[2] Roy Billinton, Ronald N. Allan.: Reliability Evaluation of Power Systems, 2nd ed. New York; Plenum Press,c, 1996.

[3] T. Ackermann.: Wind Power in Power Systems, 1st ed. New York: Wiley, 2005

[4] Leon Freris, David Infield.: Renewable Energy in Power System, 1st ed. New York: Wiley, 2008.

[5] Lundberg, S.: Evaluation of wind farm layouts, Epe journal, vol. 16, 2006

[6] Predrag Djapic, Goran Strbac.: Cost Benefit Methodology for optimal Design of offshore Transmission system, Centre for Sustainable Electricity and Distributed Generation, 2008

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